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Variability of mackerel fish catch and remotely-sensed biophysical controls in the eastern Pemba Channel

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ABSTRACT

Advances in satellite remote sensing of environmental perturbations have become important in understanding variations of ocean productivity and small pelagic fish catches. This marine resource is vital for coastal populations dependent on artisanal fishing for their income and food security, such as in coastal East Africa. In this region, the eastern Pemba Channel (Tanzania) represents a hotspot area, for a variety of marine species including small pelagics and coral reef associated species. This study examines the links between mackerel fish catch, one of the important small pelagic fish for direct consumption in the region, and changes in environmental oceanographic parameters over the period 2012–2018. The fisheries catch data is a rare local dataset, consisting of daily mackerel landings (from 2012 onwards) and supplemented by qualitative information on the mackerel fishery obtained through interviews with local stakeholders. The physical factors influencing phytoplankton biomass, and in turn, mackerel fisheries yield is investigated, using remotely-sensed chlorophyll-a (*Chl-a*) and Sea Surface Temperature (SST), together with Mixed Layer Depth (MLD) data from the high-resolution ocean model NEMO. We show that seasonal variations in mackerel landings are positively (negatively) correlated with *Chl-a* (SST) with a 1-month time lag (i.e., biophysical factors change first, mackerel stocks follow one month later). On the eastern side of the Pemba Channel, cooler SST and higher *Chl-a* are observed during the Southeast monsoon accompanied by increased mackerel landings, suggestive of enhanced productivity. Interannually, these relationships remain valid both for monthly and annual means, which confirms the close link between the variations of mackerel and biophysical conditions. Analysis of the *Chl-a* and MLD anomalies, relative to the mean, reveals that the phytoplankton blooms observed on the eastern side of the Pemba Channel, during the Southeast monsoon, are likely due to the deepening of the mixed layer, which tends to entrain cold and nutrient rich waters from greater depths to the surface. We conclude that upper ocean mixing contributes to the observed enhanced productivity along with other environmental factors. Additionally, we show how our results can be applied in the management of the mackerel resource in the Pemba Channel.

1. Introduction

There is a growing need for a more comprehensive understanding of environmental drivers of fish catches and abundance, especially under the accelerating impact of climate change and in regions where populations are dependent on living marine resources for their livelihoods (UNEP Nairobi Convention and WIOMSA, 2015; FAO, 2018; Taylor et al., 2019). Satellite remote-sensing technology, providing global coverage and long-term biological and physical observations, has been shown to successfully unravel environmental influence on fishery patterns and monitor fishery activities in the world oceans. Countries with large fishing fleets (such as France, Norway, China, Russia) have made

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available a range of satellite-derived information in near-real time to local fishers (Klemas, 2013). The most frequent indicators to inform on fish presence and abundance are chlorophyll-a (Chl-a, a proxy for phytoplankton biomass and oceanic primary production) and Sea Surface Temperature (SST) (Chassot et al., 2011). In Tasmanian waters, for example, remotely sensed SST was used to plot probable locations of mackerel schools, which improved the cost-effectivity of this fishery (Klemas, 2013). Satellite images of SST and Chl-a concentrations helped also detect dynamic oceanographic features, attractive for productivity enhancement and fish aggregations, like upwellings, ocean fronts, eddies, and filaments (Santos, 2000; Chassot et al., 2011).

In coastal East Africa, fishing activities and living marine resources are essential for food security (Taylor et al., 2019). The artisanal fishery, for small and medium pelagic fish species, has been declared as one of the most important socio-economic marine sectors in both Tanzania mainland and Zanzibar, as it supports the majority of fishers in the coastal areas of Tanzania (Maina and Osuka, 2014). However, it is also one of the most challenging marine sectors in terms of management, since a) fishing effort is widespread, b) entry into the fishery is free, and c) fishing is the principal source of income and employment in the coastal fishing communities (Daffa et al., 1997).

The marine fisheries resources from the Pemba Island shallow waters are highly utilized by the local communities in Pemba, contributing significantly to dietary protein and as a source of income for livelihood sustainability (Pemba foundation, 2016). They provide livelihoods and food security for 191 588 people in 34 of Pemba coastal communities (of whom 45% are classified as poor and over 80% are fishers), and fishers from Tanzania (Tanguy, 2018). The fisheries in the shallow waters are mainly dominated by small pelagic fish, which include mackerel (Scombridae), anchovies (Engraulidae) and sardines (Clupeidae) (Breuil and Bodiguel, 2015). The Indian mackerel (Rastrelliger kanagurta) is the most prominent mackerel species caught in Pemba waters (Jiddawi and Ohman, 2002; Breuil and Bodiguel, 2015).

The mackerel fishery of Pemba Island is mainly conducted along the eastern part of the Pemba Channel (western coast of Pemba Island), where the waters are relatively calm and shallow with surface temperatures of at least 18 °C (Breuil and Bodiguel, 2015). Less fishing is conducted along the eastern side of the island and in the offshore waters as these waters tend to be very rough and risky for the fishers (Pemba foundation, 2016). Indeed, mature mackerel fish are found in bays and lagoons (like the eastern Pemba Channel) and waters rich in plankton (Bhendarkar et al., 2014). Mackerel fish species are considered to be planktivorous, with zooplankton being the most dominant proportion of mackerel food, followed by phytoplankton, algae and fish larvae (Hulkoti et al., 2013; Das et al., 2016). The choice of food depends upon the life stages of the fish (Bhendarkar et al., 2014). The early stages are highly dependent on phytoplankton as the main food source, and as they grow to adulthood their food preference switches to zooplankton (Hulkoti et al., 2013).

The mackerel fishery in Pemba is mainly artisanal, involving local fishers who use small motorised or non-motorised vessels for fishing in the nearshore waters that are easily accessible (Jiddawi and Ohman, 2002). Traditional fishing vessels such as dhow, small wooden boats and canoes that can be operated by engines, sails or paddles are normally used. Ring nets/purse seines with lamps are important gears for mackerel and other small pelagic fishing in the region (Jiddawi and Ohman, 2002; Muhando and Rumisha, 2008). Mackerel in Pemba are caught as target or as bycatch, especially in other small pelagic fishing activities such as for anchovies and also large pelagic fishing such as for tuna. On some occasions they are caught as bycatch in the reef fishery as they search for food around the reef ecosystems (Breuil and Bodiguel, 2015). Depending on the season and oceanic conditions, the fishers use their local knowledge and experience in migrating from one place to another in search for these resources (Wanyonyi et al., 2016). The traditional knowledge of the local fishers has been of great importance in coping with the changing oceanic conditions (cf. section 2.1 for more details).

Few studies have focused on the environmental factors influencing productivity in the Pemba Channel. Bakun et al. (1998) showed that wind-driven upwelling is occurring during the NE monsoon along the western side of the Pemba Channel. During the SE monsoon, Barlow et al. (2011) suggested from in-situ data that eddy activity is likely responsible for enhanced productivity in the eastern Pemba Channel. Painter et al. (2020) showed evidence of localized upwelling in that same part of the Channel from in-situ data sampled in the SE monsoon. These reported processes likely sustain food availability for small and medium pelagics such as mackerel and thereby their catch variation.

Although remote sensing approaches are increasingly being used to assess marine phytoplankton biomass variability, bloom timing and linkages with fish catch in many parts of the world (e.g. Santos, 2000; Platt and Sathyendranath, 2008; Wall et al., 2009; Raitsos et al., 2015; Kassi et al., 2018), such methods have not yet been applied in the Pemba Channel. It is even less common for the impact of environmental parameters on fish catch to be assessed and such an assessment is completely non-existent for the mackerel fishery. This study aims at filling this gap by exploring long-term satellite data coupled with high-resolution ocean model outputs to better understand the influence of environmental parameters on the abundance of mackerel catches along the eastern side of the Pemba Channel. We examine seasonal and interannual relationships between mackerel and satellite Chl-a; and between mackerel and satellite SST. The mechanistic links between the observed variability in Chl-a concentrations and local physical factors (satellite SST and modelled Mixed Layer Depth [MLD]) are further assessed. A fishers' survey is also explored to document local perspectives on the mackerel fishery to support the catch data. Finally, we discuss how the results can inform fisheries management and translate into practices for improved monitoring of this valuable resource.

2. Materials and Methods

2.1. Study region and ocean dynamics

The Tanzanian waters can be distinguished in the Western Indian Ocean by their islets, islands and Channels. The Pemba Channel separates the Tanzanian mainland from Pemba Island and differs from the Zanzibar and Mafia Channels, which are located on the central and southern parts of Tanzania waters, respectively (Fig. 1a). The Pemba Channel is characterized by deep waters (~800 m deep), while the Zanzibar and Mafia Channels are shallow (less than 60 m deep) (Fig. 1). The Pemba Island shore is highly indented (Fig. 1b) with a relatively wider stretch of inshore fringing reefs, a number of small islets that provide a good breeding and recruitment area for different fish species and a variety of marine animals (Grimsditch et al., 2009). The coral reefs along the eastern Pemba Channel are among the most diverse reefs in East Africa (Grimsditch et al., 2009). Their high biological diversity has attributed to high primary productivity that supports marine life, including various fish species (Grimsditch et al., 2009).

The eastern part of the Pemba Channel is well known for a variety of fisheries activities, including sport fishing for billfish and marlin, and a commercial fishery for tuna, tuna-like species and kingfish (Breuil and Grima, 2014; Groeneveld, 2016). Due to its importance in fisheries and marine biodiversity (Tanguy, 2018), a large part of the eastern Pemba Channel has been declared as a marine conservation area (Pemba foundation, 2016), designated as Pemba Channel Conservation Area (PECCA). PECCA has a total area of about 1100 km^2, enclosing the shallow waters and the islets along the eastern side of the Pemba Channel (see Fig. 1b).

The eastern Pemba Channel has diverse groups of fish such as mackerel (Scombridae), sardines (Clupeidae), groupers (Epinephelinae), red snapper (Lutjanus) and parrot fish (Scaridae)) that are consumed domestically. Other fish species including tuna (Thunnini), marlin (Istiophoridae), barracuda (Sphyraena), kingfish (Scomberomorus), swordfish (Xiphias), anchovies (Engraulidae), lobster

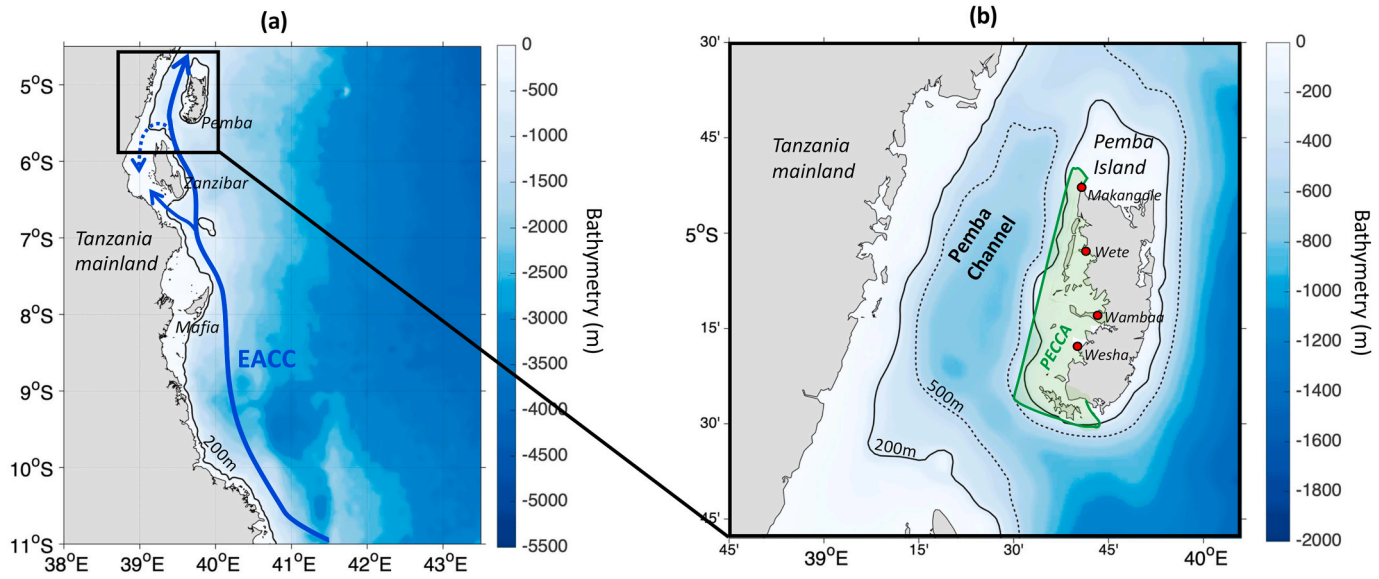


Fig. 1. a) Bathymetry (m) of the Tanzanian waters from 38.5 to 43.5°E. Schematic of the surface currents near Tanzania based on Semba et al. (2019). The East African Coastal Current (EACC) flowing northward year-round is presented with solid blue arrows. The EACC reversal in the Zanzibar Channel during the NE monsoon is shown with a dashed blue arrow. The 200m isobath marking the continental shelf is highlighted with a solid black line. **b)** Bathymetry (m) of the Pemba Channel. The ecologically significant marine area along Pemba west coast, PECCA (Pemba Channel Conservation Area), is highlighted with a light green shade. The four districts where the survey respondents were interviewed are indicated by the red dots. The 200m and 500m isobaths are shown with a solid and dashed black lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Nephropidae) and octopus (Octopoda) are caught for commercial purposes (Feidi, 2005; Grimsditch et al., 2009). Mackerel is among the most important fish groups in Pemba and more widely in Tanzanian coastal waters (Breuil and Bodiguel, 2015). Most of the mackerel catches from PECCA are sold in the local trade markets in Zanzibar (Pemba or Unguja) and other nearby coastal towns/cities along the Tanzania mainland (Breuil and Bodiguel, 2015).

The oceanic conditions in the Tanzanian waters as a whole are mainly controlled by the large-scale monsoon winds (Swallow et al., 1991). These winds influence the productivity via local and remote forcing on the surface circulation (Jebri et al., 2020), which is dominated by the East African Coastal Current (EACC) (Semba et al., 2019; Sekadende et al., 2020). The winds change on a seasonal basis along the East African coastal region (Mahongo et al., 2011). The Northeast (NE) monsoon lasts from December to February while the Southeast (SE) monsoon runs from May to September. March–April and October–November are regarded as transition periods when the winds change direction from NE to SE and vice versa (Okoola, 1998; Funk et al., 2016). The NE monsoon is characterized by weak winds, elevated temperatures, and calm ocean conditions (Mayorga-Adame et al., 2016; Shaghude et al., personal communication). The reduced NE winds generate a weak EACC with speeds of around 0.8 m/s (Semba et al., 2019) and a northward flow in the Pemba Channel and along Tanzania, except in the Zanzibar Channel where it reverses to a southward flow (Fig. 1a; Mayorga-Adame et al., 2016). By contrast, the SE monsoon is characterized by strong winds, low temperatures and rough seas (Mayorga-Adame et al., 2016). During this season, the EACC continues to flow northward but intensifies up to 2 m/s under the influence of stronger SE winds (Semba et al., 2019).

2.2. Satellite data

The satellite data used for this study consists of Chl-a and SST products. The remotely-sensed Chl-a dataset used is obtained from Ocean-Colour Climate-Change Initiative project (OC–CCI version 3.1; http://www.esaoceancolour-cci.org/). This global dataset is the most consistent timeseries of multi-satellite ocean colour data (Racault et al., 2017). It is distributed as monthly means at 1 km and 4 km horizontal resolution. The 1 km Chl-a monthly means, available from September 1997 to December 2016, are used to plot the seasonal climatological spatial patterns over the Pemba Channel (cf. section 3). The 4 km Chl-a monthly means, available from September 1997 to December 2018, are used to examine the seasonal and interannual temporal patterns over the area of interest during 2012–2018 (cf. section 3). The 2012–2018 period is chosen to match the time period of the available fish catch records. Note that to derive the climatological (mean) state of Chl-a spatial patterns at high spatial resolution, the 1997–2016 period at 1 km resolution is used. A longer timeseries helps derive an improved climatology and a higher spatial resolution leads to better defined spatial patterns.

The SST dataset used here consists of the multi-satellite global product spanning the period June 2002–July 2018 acquired from the JPL MUR MEaSUREs Project (2015) version 4.1 (https://podaac.jpl.nasa.gov/dataset/MUR-JPL-L4-GLOBv4.1?ids=&values=&search=MUR). This SST product is available on a daily basis and at 1 km resolution. We calculated the monthly means for the study region to construct a climatology of SST spatial patterns over the period June-2002-July-2018. Additionally, the seasonal and interannual temporal SST variations are examined between 2012 and 2018, in accordance with the fish catch data. The mean SST spatial patterns are calculated using the climatology over the longer time period 2002–2018, for an improved estimate of the mean (climatological) state.

2.3. Model data

Mixed Layer Depth (MLD) data from the global high resolution (1/12°) ocean model NEMO (Nucleus for European Modelling of the Ocean, version 3.6) (Madec & NEMO System Team, 2015) was used to provide complementary information about the mechanisms of the productivity over the study area. The NEMO model has been successfully used and validated over the East African coastal area (Jacobs et al., 2020; Jebri et al., 2020). NEMO has 75 vertical levels, which are spaced more finely near the surface with 22 levels in the top 100 m. The modelled MLD data is available as 5-day means over the period 1958 to 2015. The MLD in

the model is calculated as the first depth where the temperature is at least 0.1 °C different from the surface temperature. Here, we utilize the MLD monthly means for the period 2012–2015 to be consistent with the fisheries and satellite data. The missing time period 2016–2018 in the MLD data, was removed from the Chl-a timeseries for comparison purposes between both variables.

2.4. Mackerel landings dataset

Mackerel landings by artisanal fishers on the eastern side of the Pemba Channel, recorded in kg of wet weight per day, from 2012 to 2018, are used in this study. These catch data were acquired from the Pemba fisheries office (Ministry of Agriculture, Natural resources, Livestock and Fisheries (MANRLF)), and are aggregated from four districts on Pemba Island. In each district, there is one important and formal small pelagic landing site where catches from all areas within the district are landed. These landing sites include: Tumbe (Makangale district), Wete (Wete district), Wesha (Chakechake district) and Mkoani (Wambaa district) (cf. Fig. 1b). Daily recording of the data is done for 16 days in each month. The 16 days for data recording are mostly selected to fit the new moon period when the nights are darker, making fishing with lamps more efficient (the most common small pelagic fishing practice on Pemba Island). Monthly mackerel catches are estimated by averaging the available daily landings for each month over the full-time record (2012–2018) and correlated with satellite derived data.

2.5. Cumulative sums analysis

To further explore the variability in the mackerel catch and Chl-a timeseries, the data were deseasonalised (i.e. the seasonal cycle removed) and the Cumulative Sums method applied following two steps explained below. Firstly, the overall monthly climatological means were calculated for each calendar month for both variables (Chl-a and mackerel) during the period 2012–2018. Then, the monthly anomalies were calculated by subtracting each climatological monthly mean (e.g., January overall $Mean_{2012\text{-}2018}$) from each month (e.g., Jan_{2012}, Jan_{2013} …. Jan_{2018}) of the timeseries. The deseasonalisation (calculation of anomalies) is a simple statistical method for removing the seasonal component of a timeseries, which serves the purpose of further analysing a timeseries, by eliminating the seasonal component, and thus isolates the cyclical deviations from the trend (independently of the seasonal components). Secondly, the Cumulative Sums method was applied on the timeseries anomalies, to emphasize subtle temporal patterns and highlight the variability in both timeseries (in this case the Chl-a and mackerel variability). The cumulative sums statistical method summarizes the major changes by smoothing high frequency variability and highlighting changes in local mean values along the timeseries. The increasing temporal trends are shown as successive positive anomalies, producing an increasing slope, while decreasing temporal trends are shown as successive negative anomalies, producing a decreasing slope (Supplementary Fig. 1). When applied on two different variables, the variability trend of the two timeseries can be compared (in this case the Chl-a and mackerel timeseries). This method has been repeatedly used to highlight major temporal changes in monthly Chl-a anomalies of timeseries (e.g., Tilstone et al., 2015; Raitsos et al., 2014; McQuatters-Gollop et al., 2008).

2.6. Fishers' survey design and data

The fishers' interview survey was conducted for fourteen days from 1st to August 14, 2019 to generate qualitative information on mackerel catch trends, their seasonality and abundances from local fishers along the eastern side of the Pemba Channel. The survey design is implemented using two methods, the Key Informant Interview (KII) and the Nominal Group Technique (NGT). The NGT is a structured group-based technique used to build consensus. Thirty-nine fishers with at least 20-years of experience in fishing activities were selected to create groups of 6 members as recommended by Huge and Mukherjee (2018). One group discussion was carried out at each of the four landing sites (Fig. 1b) where the experienced fishers were asked to individually reflect and generate ideas based on pre-determined structured questions. The ideas were then ranked and prioritized by the group members. Interviews with Key Informants were conducted to provide information on various issues related to the mackerel fishery trends in the eastern Pemba Channel (See Appendix for more details on the questionnaire used). This involved interviews with fisheries officers, Shehia Fisheries Committee (SFC) leaders, fish catch data recorders, influential fishers and other important stakeholders within the sites. A total of 15 individuals were interviewed in the KIIs. Separate checklists were prepared for fisheries officers, SFC leaders and data recorders. Four sites/villages were selected (one from each of the 4 administrative districts) depending on their relevance in the mackerel fishery.

Content analysis was used to analyse the KII and NGT qualitative information following Stone et al. (1966). The recorded dialogues were broken down into the smallest meaningful and expressive units of information to obtain value and attributes of respondents. Both KII and NGT were used to provide relevant qualitative information on mackerel fish catch exploited by local fishers along the eastern side of the Pemba Channel. From the NGT discussions, all groups that were interviewed from different sites (Makangale, Wete, Wesha, Wambaa) described the seasonal abundance of Mackerel in the eastern Pemba channel and the preference for small pelagic fish in direct consumption by local communities (cf. Fig. 2).

3. Results and discussion

3.1. Seasonal spatial distribution of phytoplankton biomass and SST

The seasonal spatial distributions of satellite *Chl-a* and SST in the Pemba Channel over the climatological periods 1997–2016 and 2002–2018, respectively, are shown in Fig. 3. The *Chl-a* and SST fields vary significantly along the Channel between the SE and NE monsoons. The SE monsoon shows more productive features over most of the Channel.

In the central and eastern parts of the Pemba Channel, elevated Chl-a (up to 0.55 mg/m^3 or higher) and lower SST (down to 26 °C) are observed during the SE monsoon (Fig. 3b). By contrast, these areas are characterized by lower phytoplankton biomass (<0.2 mg/m^3) and warmer waters (up to 28.7 °C) during the NE monsoon. The western side of the Pemba Channel experiences the presence of relatively more productive waters than the eastern side during the NE monsoon, with cooler SSTs of around 27.8 °C and Chl-a concentrations of about 0.35–0.55 mg/m^3 (Fig. 3a, c). These seasonal patterns are coherent with the recent findings in Tanzanian waters reported in Shaghude et al. (Personal Communication). Additionally, satellite images reveal a localized patch of cooler waters associated with higher Chl-a, relative to the surroundings waters, confined along the eastern Pemba Channel coastline during the SE monsoon (Fig. 3b, d).

The higher productivity of the SE monsoon along the whole Tanzanian and Kenyan coastal band has been linked with dynamic upwelling and advection processes, which act through the EACC (Jebri et al., 2020). However, because of its localized nature, the colder and higher Chl-a feature along the eastern Pemba Channel (Fig. 3b, d) is likely to be independent from these larger scale EACC upwelling and advection processes. Furthermore, this hotspot location of phytoplankton biomass (see dotted black box on Fig. 3b) encompasses the PECCA zone where there is high coral reef and associated species' diversity and a variety of other fish species (Tanguy, 2018). For instance, high fishing activity for mackerel and other small pelagics occur regularly (Breuil and Bodiguel, 2015).

It can be argued that satellite-derived Chl-a observations in shallow coastal zones like the eastern Pemba Channel, have some limitations.

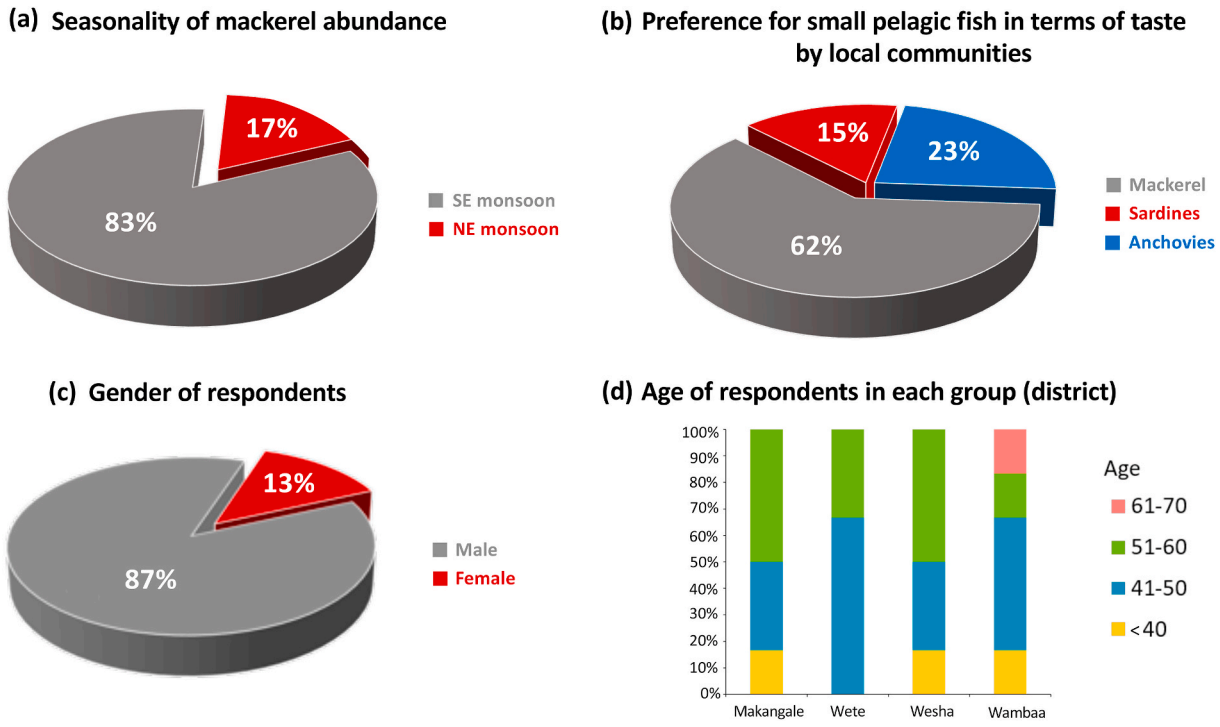


Fig. 2. **(a)** Percentage of the seasonality of mackerel fish catch abundance from the respondents' perspectives survey. **(b)** Percentage of the preference of local communities for small pelagic fish (mackerel, sardines and anchovies) in terms of taste as viewed by the survey respondents. **(c)** Gender and **(d)** age of the respondents in each group (district).

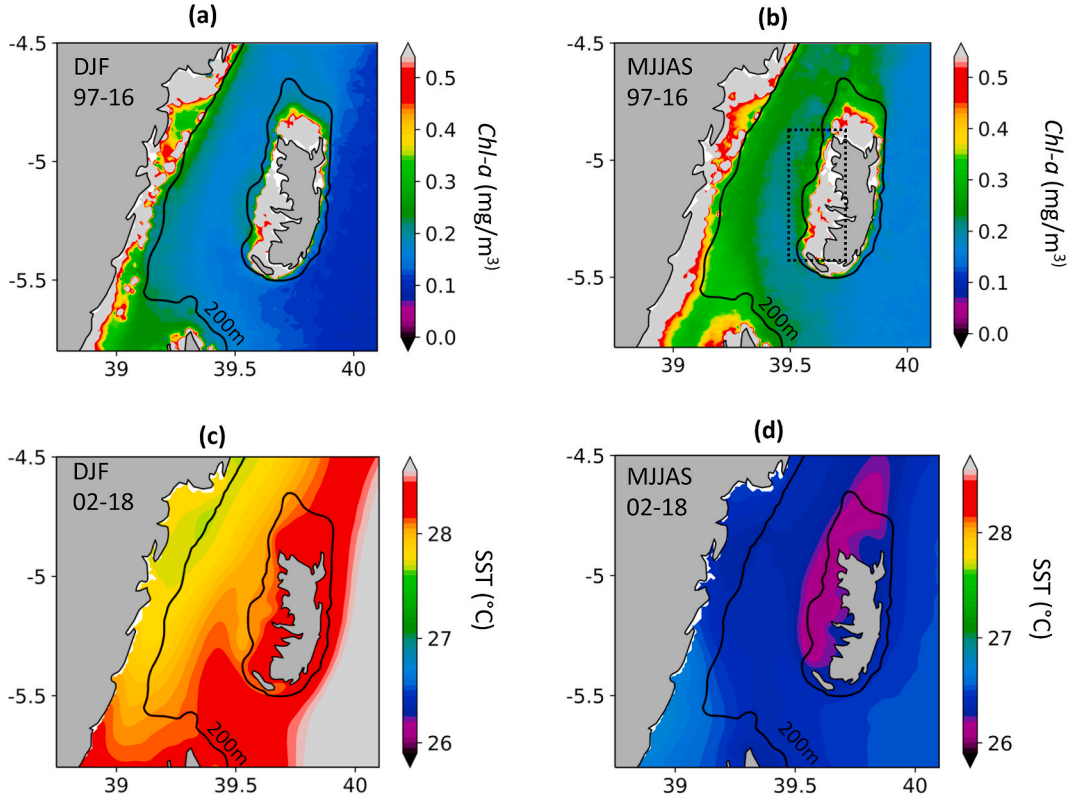


Fig. 3. Climatological Chl-a (mg/m^3) and SST (°C) spatial patterns during the NE and SE monsoons in the Pemba Channel over the periods 1997–2018 and 2002–2018 respectively. Chl-a averaged from Decembers to Februarys (May to September) of 1997-2018 and representative of the NE (SE) monsoon are presented in panels **(a)** and **(b)** respectively. SST averaged from Decembers to Februarys (May to September) of 2002-2018 and representative of the NE (SE) monsoon are presented in panels **(c)** and **(d)** respectively. The 200m isobath marking the continental shelf is highlighted with a black solid line. The dotted black box on panel (b) indicated the area from which the timeseries of Chl-a and SST shown in Figs. 3–5 are derived. This box encompasses largely the mackerel fishing zone.

These limitations result in a possible overestimation of Chl-a concentrations, as well as being indicative of the phytoplankton biomass only within the first optical depth, and not the complete vertical water column. The overestimation of satellite Chl-a concentrations in shallow optically complex Case II waters is mainly due to the influence of suspended material and dissolved organic matter, which may result in high water leaving radiance (IOCCG, 2000). However, the high Chl-a values of these shallow coastal waters could also be a sign of highly productive coral reef zones (Raitsos et al., 2017). This is the case of the eastern Pemba Channel which is a zone of abundant coral reefs (Chauka, 2012; Pemba foundation, 2016; Chauka et al., 2016) and where the satellite Chl-a values near the coast reach elevated values (>0.6 mg/m^3 Fig. 3a and b). However, validation of satellite derived Chl-a is hindered by the lack of sufficient spatiotemporal distribution of in-situ Chl-a data, a few local studies have focussed on such comparisons in the region. Peter (2013) reported significant positive correlations between satellite and in-situ Chl-a during both the SE and NE monsoons along the coastline of the western Pemba Channel (shallow area). The values reported by Peter (2013) ranged from 0.1 to 0.9 mg/m^3, which are comparable within the order of magnitude of Chl-a values observed here (cf. Fig. 3).

For the rest of the analysis, the focus is on the variability of the mackerel catches and their links to biophysical factors within the eastern side of the Pemba Channel.

3.2. *Temporal seasonal variations in mackerel catch and links with Chl-a and SST*

The mackerel seasonal cycle (blue line on Fig. 4 a, c) shows a distinct variability, with higher catches around the SE monsoon compared to the lower catches around the NE monsoon. The seasonal landings reach a maximum in October, with 95 tonnes, towards the end of the SE monsoon (blue line on Fig. 4a, c). The lowest seasonal landings are

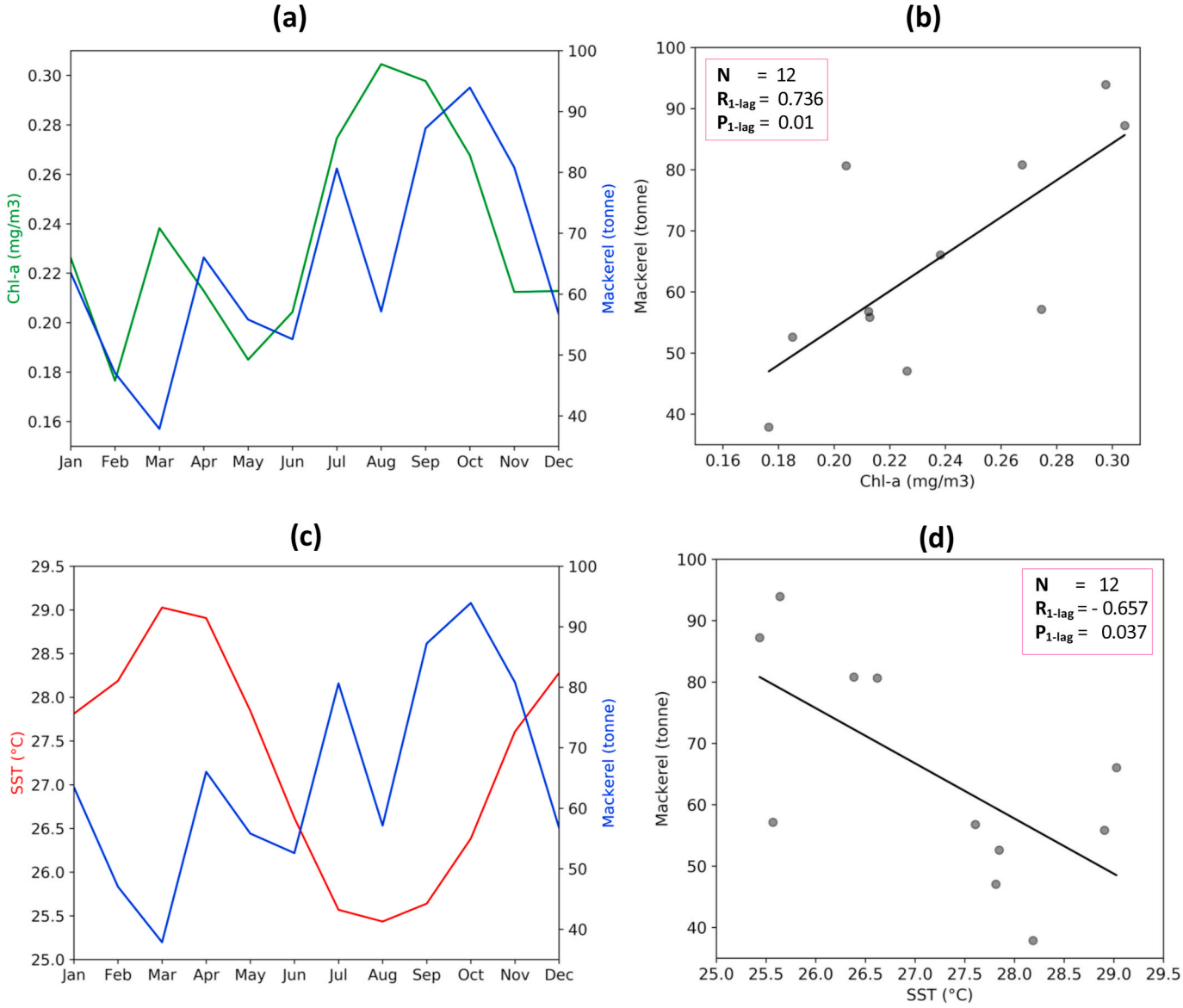


Fig. 4. Seasonal cycles of **a)** mackerel (blue line) vs Chl-a (green line) and **c)** of mackerel (blue line) vs SST (red line) in the eastern Pemba Channel box over the period 2012–2018. Their respective scatter plots are shown on panels **b)** and **d)**. The Pearson correlation coefficients at 1-month lag (called here $R_{1\text{-lag}}$), p-values at 1 month lag (called here $P_{1\text{-lag}}$) and number of points in the timeseries (N) of the two parameters at 1-month lag are indicated in the pink boxes. Note that the p-value tests the hypothesis of no correlation. The p-value is the probability of getting a correlation as large as the observed value, when the true correlation is zero. If the p-value is less than 0.05, then the correlation R is significant at the 95% confidence level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recorded in March, with 37 tonnes, at the end of the NE monsoon.

The higher catches during the SE monsoon are likely to be influenced by food availability (phytoplankton) indicated by higher Chl-a concentrations during this season (Fig. 4a). A number of studies conducted along the Pemba Channel have also reported on the abundance of phytoplankton around this season (Barlow et al., 2011; Peter, 2013; Sekadende et al., 2020, Painter et al., 2020, Shaghude et al., Personal Communication). The maximum significant correlation of mackerel catches with Chl-a is observed at a 1-month time lag (R = 0.736, P-value = 0.01) (Fig. 4b). The Chl-a is at its maximum concentrations of ~0.3 mg/m^3 in August–September, a month prior to the highest peak in mackerel catch of 95 tonnes (Fig. 4a). This suggests that the mackerel depends on phytoplankton (Chl-a) for food, and so proliferate when phytoplankton are abundant in this region. The observed lag can be explained by the feeding behaviour of mackerel (Krishnakumar et al., 2008). Zooplankton contribute about 41% of the total dietary requirements for mackerel followed by phytoplankton that contribute about 37% (Hulkoti et al., 2013). During the larval stages, the mackerel prefer to feed on phytoplankton, and as they turn into adults their main food source shifts to zooplankton (Krishnakumar et al., 2008; Hulkoti et al., 2013). Consistent with the observed one-month time lag, an increase in Chl-a will in turn lead to an increase in zooplankton (which feed on the phytoplankton) with a slight time lag due to their slower growth rate (e.g. Li et al., 2019).

Mackerel catches are higher during the SE monsoon, which is characterized by cooler SST, than during the NE monsoon, which is a period of warmer SSTs (Fig. 4c). The strongest significant negative correlation between SST and mackerel is at one-month lag with a correlation coefficient of −0.657 and a p-value of 0.037 (Fig. 4d). The coolest SST is observed from August–September (25.4–25.7 °C), which is one month prior to the highest peaks of mackerel catches (88–95 tonnes) (Fig. 4d). These findings are consistent with a number of studies showing that mackerel tend to be more abundant with lower temperature conditions and are therefore more abundant during the season when the SST drops (McClanahan, 1988; Musallam et al., 2006; Hulkoti et al., 2013; Breuil and Bodiguel, 2015). Additionally, results of the fishers' survey confirmed that mackerel are caught in highest abundance during the SE monsoon (Fig. 2a), particularly from August to October. The main reason given is that the cool surface water attracts mackerel to the surface and nearshore waters making it more accessible to artisanal fishers. The fishers observed that mackerel were either targeted or caught by ring nets/purse seines as bycatch from other small pelagic fishing especially that of anchovies that are more abundant in the eastern Pemba Channel.

Having considered the climatological seasonal cycle of mackerel, *Chl-a* and SST along the eastern Pemba Channel, it can be concluded that lower (higher) SST, is linked with higher (lower) *Chl-a* and, with a one-month lag, with higher (lower) mackerel catches. Next the interannual variability of these relationships is examined using both monthly and annual means.

3.3. Interannual variations in mackerel catch and links with Chl-a and SST

The annual means of mackerel versus *Chl-a* and SST (Fig. 5a and b) display somewhat similar behaviour to the seasonal cycles shown in Fig. 4 (a, c), with in-phase (contrasting) mackerel and *Chl-a* (SST) patterns. The most obvious observation to note about the *Chl-a* annual means and mackerel annual catches is that they both dip sharply in 2015, at a time when SST peaks (Fig. 5a and b). Overall, the SST annual means and mackerel annual catches both appear to exhibit a weak increasing trend but not in *Chl-a* over the period (Fig. 4a and b). However, with only 7 years of data it is difficult to draw any strong conclusions based solely on annual means.

The total catch of mackerel recorded from 2012 to 2018 indicates a slightly rising trend, but with large variability (see Fig. 5c and d). The mackerel and *Chl-a* monthly means display an overall coherent (positive) relationship (Fig. 5c). It is interesting to note that the highest monthly catch is recorded in August 2017 at 177 tonnes which corresponds to the highest peak of *Chl-a* (0.45 mg/m^3) in the same month. Another high peak of 176 tonnes in September 2018 also corresponds to the second highest peak of *Chl-a* (0.39 mg/m^3). Furthermore, the

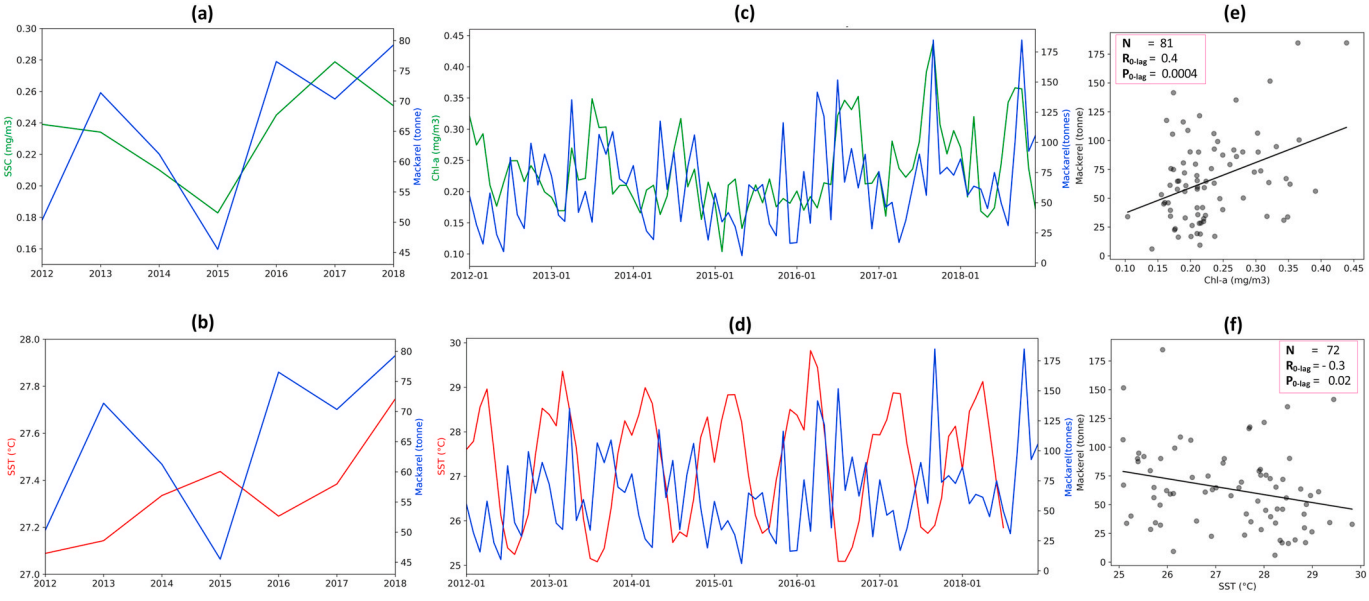


Fig. 5. Annual means of **a)** mackerel (blue line) vs Chl-a (green line) and **b)** mackerel (blue line) vs SST (red line) from 2012 to 2018 over the eastern Pemba Channel box indicated on Fig. 2b. Monthly means of **c)** mackerel (blue line) vs Chl-a (green line) and **d)** mackerel (blue line) vs SST (red line) from 2012 to 2018 over the eastern Pemba Channel box. Their respective scatter plots are shown on panels **e)** and **f)**. The Pearson correlation coefficients at no lag (called here $R_{0\text{-}lag}$), p-values at no lag (called here $P_{0\text{-}lag}$) and number of points in the timeseries (N) of the two parameters are indicated in the pink boxes. Note that the p-value tests the hypothesis of no correlation. The p-value is the probability of getting a correlation as large as the observed value, when the true correlation is zero. If the p-value is less than 0.05, then the correlation R is significant at the 95% confidence level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cumulative sums method was applied to the anomalies (removal of the seasonal cycle) of mackerel fisheries yield and *Chl-a* to further decompose the signal by reducing the high frequency variability (see section 2.5 in Materials and Methods for more details). Positive temporal trends are highlighted by consecutive positive anomalies (increasing slope), whereas temporal trends are shown as consecutive negative anomalies (decreasing slope). The cumulative sums of anomalies between mackerel and *Chl-a* indicates the solid nature of the relationship, as the interannual variability of both variables oscillates in a parallel way (not only within a year) at a great degree (Supplementary Fig. 1).

The SST and mackerel monthly means (Fig. 5d) show an overall inverse relationship, suggesting that the fall (rise) in mackerel catches is linked to the rise (fall) in SST. The corresponding correlation for the *Chl-a* versus mackerel monthly means is 0.4 and significant at the 95% level with a p-value of 0.0004 at zero lag (Fig. 5e). The SST and mackerel monthly means show a significant negative correlation ($R = -0.3$, *P-value* $= 0.02$) at zero lag (Fig. 5f).

Overall, the peak in mackerel catches occur in sync with the peak in *Chl-a* when SST is lowest and *vice versa* (Fig. 5c and d). This is similar to what was observed for the seasonal cycles, i.e. that mackerel were abundant in coherence with the abundance of phytoplankton and cooler waters (cf. section 3.2 above). Overall, the mackerel catches are more abundant from June to November, though in some years high catches were recorded in April (e.g. 2013, 2014, 2016). The high catches in the June–November period coincide with peaks in *Chl-a* when the Pemba Channel waters experienced higher phytoplankton biomass (Fig. 5c). The high catches in April in some years, could have been influenced by a secondary small peak in phytoplankton observed in March as in the seasonal cycles (Figs. 4a and 5c).

Mackerel catches increased in 2016 and 2018 despite the relative decline of Chl-a and rise of SST (Fig. 5a–d); this might be attributed to increased effort in mackerel/small pelagic fisheries in recent years. However, the mackerel landings data used here are nominal catches rather than catch per unit effort, which may not always reflect stock abundance, as their fluctuations could be generated by other factors like overfishing (Froese et al., 2012). The corresponding effort data for these landings are not available and the landings (nominal catch) are the only data accessible, from the Fisheries Department in Pemba. The landing data could, potentially, indicate resource availability, since landing trends are generally coherent with biomass trends from fully assessed stocks (Froese et al., 2012) and as shown in studies which link satellite Chl-a and marine fish catch (Kassi et al., 2018; Jebri et al., 2020). This "landing-resource" relationship, however, cannot be absolutely confirmed in the absence of effort data, as the case for our region of interest. An insight on the effort was provided from the results of KII and NGT interviews where fishers of different ages and gender from four districts were interviewed (Fig. 2c–d), revealed a rapid increase in the number of fishers in recent years. The fishers explained that there were few alternative activities/livelihoods, high unemployment levels on the island, and so people focused more on fishing, leading to overharvesting of the resources. The local communities preferred mackerel over other small pelagic fishes, such as sardines and anchovies, because of their better taste (Fig. 2b). The reasoning of fishing effort impact on the recent catches was also supported by the fisheries frame survey report of 2016 (Department of Fisheries Development, 2016). The report showed that as the number of fishers increased, the overall total catch rose despite the decline in individual catches landed by a fishing vessel. The number of fishers, vessels and gears had increased tremendously in the frame survey of 2016 compared to one made in 2007. During 2007, 15 680 fishers were recorded against 18 047 in 2016, an increase of 2367 fishers. The vessels mostly used for small pelagic fishing such as boats had a 100% increase, and dhows a 69% increase by 2016 from the lower numbers in 2007 (Department of Fisheries Development, 2016).

3.4. Upper-ocean mixing effect on phytoplankton biomass variations and bloom timing

The seasonal cycles of *Chl-a* and SST in the eastern Pemba Channel show contrasting behaviours in the SE and the NE monsoons (Fig. 6a). The highest *Chl-a* concentrations (0.32 mg/m^3) occur in August during the SE monsoon (Fig. 6a). This period of strong bloom is associated with the coolest annual SST (~25.4–25.7 °C) attained between July and September (Fig. 6a), suggesting that lower ocean temperature conditions tend to favour phytoplankton biomass abundance, and primary productivity. By contrast, weak/no bloom periods, characterized by lower *Chl-a* values (<0.23 mg/m^3), are seen during the NE monsoon months accompanied by warmer SST (>27.7 °C) (Fig. 6a). The higher temperature conditions (29 °C) during March (transition from the NE the SE monsoon), however, did not limit the peaking of phytoplankton biomass during this time, where a relatively small peak of *Chl-a* of 0.24 mg/m^3 is observed (Fig. 6a). Overall, the SST is significantly correlated with the bloom timing ($R = -0.749$, *P-value* $= 0.05$) (Fig. 6b). This inverse relationship confirms that the rise in temperatures led to the decline in *Chl-a* concentrations and *vice versa*.

Fig. 6c shows the climatological seasonal cycles of *Chl-a* and Mixed Layer Depth (MLD), over the eastern Pemba Channel box (cf. Fig. 3b). The cycles suggest that the MLD deepens between April and August (down to 21 m) and that the *Chl-a* responds almost simultaneously with increase between May and August. This response could be related to the deepening of the mixed layer leading to nutrients being brought up into the surface waters promoting phytoplankton growth. The fact that the *Chl-a* is positively and significantly correlated to the MLD ($R = 0.624$, *P-value 0.036*) (Fig. 6d) strengthens the argument that this particular area of the Channel is likely influenced by the mixing that deepens during the SE monsoon and entrains cold water to the surface (Fig. 6a).

In tropical ecosystems, the interannual variability of Chl-a concentrations is vastly determined by the strength of vertical mixing in the water column (Gittings et al., 2018). To examine the interannual variability in the Chl-a-MLD relationship, Fig. 6e shows Chl-a and MLD monthly anomalies from 2012 to 2018 relative to their respective seasonal cycles. Note that the MLD timeseries stops in December 2015 because that is when the model run ends. Although there are high fluctuations in the MLD and Chl-a anomalies, the positive MLD anomalies (meaning deeper MLD) which can reach up to 6 m, coincides most of the time with positive Chl-a anomalies (increase in phytoplankton biomass). For instance, from May to August 2013 with peaking of positive MLD and Chl-a anomalies. The opposite situation, i.e. negative MLD anomalies (i.e. shallower MLD) coinciding with negative Chl-a anomalies (reduction in phytoplankton biomass), occurs from May to August 2015, where the largest MLD negative anomaly was observed (−7 m), leading to a Chl-a decrease of about - 0.1 mg/m^3. The correlation between the MLD and Chl-a remains significant in terms of monthly anomalies ($R = 0.421$, p-value $= 0.004$) but slightly weaker than at the seasonal scale (Fig. 5e).

The observed relationships between the Chl-a with MLD and SST (Fig. 6) indicate that phytoplankton biomass variations in the eastern Pemba Channel are at least partly influenced by upper ocean mixing. The deepening of the MLD is likely triggered by strong SE winds which blow from south to north towards the East African coast during the SE monsoon (e.g. Schott et al., 2009). Deepening of the mixed layer during the SE monsoon coincides with cooling of surface waters (low SST). This is an indication that nutrient-rich deep cold waters are likely brought to the surface and in turn promote phytoplankton growth (increase in Chl-a). Strong response of Chl-a to the deepening of the MLD is a typical feature of tropical ecosystems variability (e.g. Gittings et al., 2018). When the primary production is limited by nutrients, seasonal deepening of the mixed layer leads to nutrient entrainment and enhanced Chl-a (e.g. Bradford-Grieve et al., 1996). Furthermore, the presence of upwelling and advection have been previously reported as important contributors to phytoplankton productivity in this area (cf. Jebri et al.,

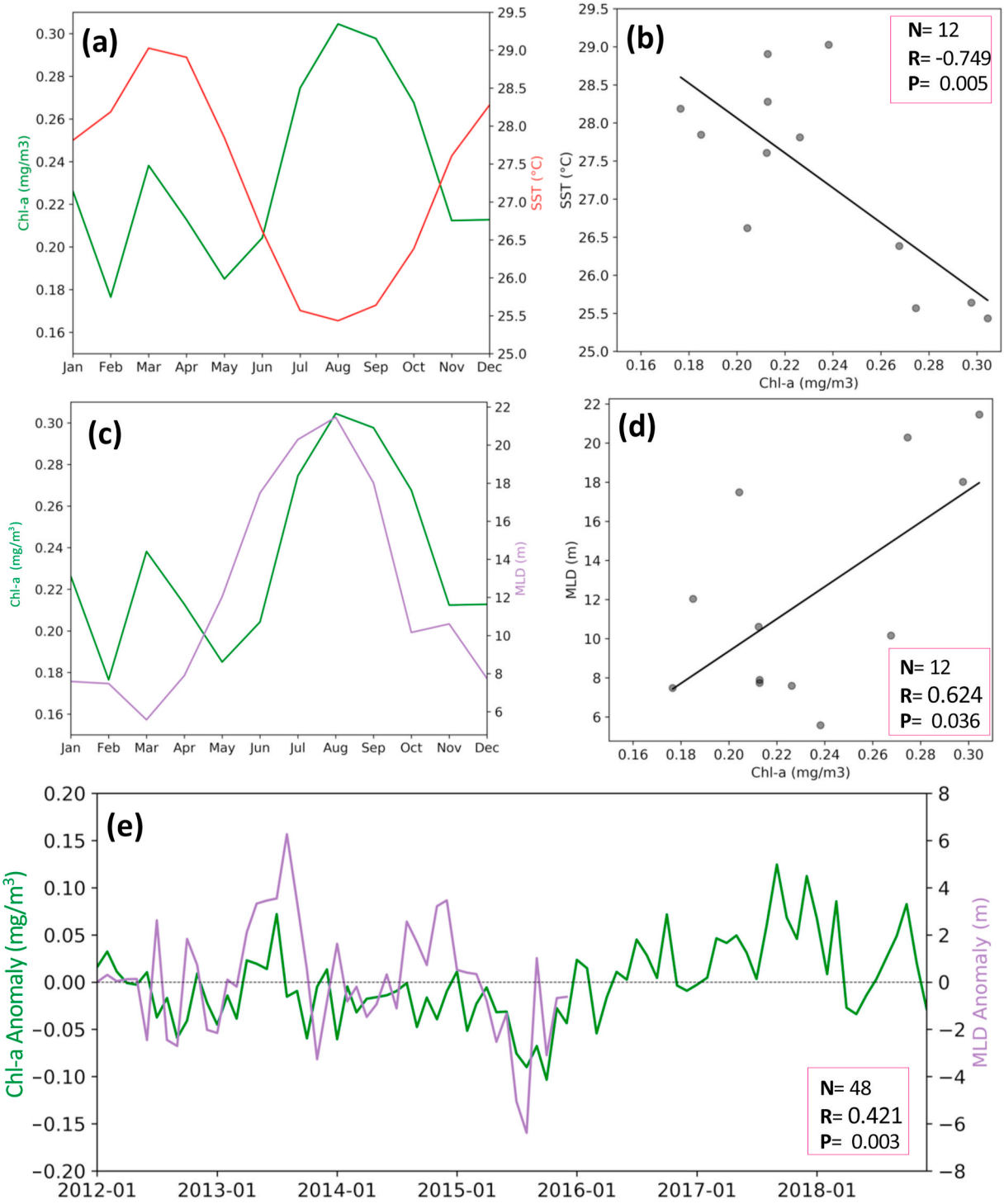


Fig. 6. Seasonal cycles of **a)** Chl-a (green line) vs SST (red line) and **c)** of Chl-a (green line) vs MLD (purple line) in the eastern Pemba Channel box over the period 2012–2018, except for the MLD which spans the period 2012–2015. Their respective scatter plots are shown on panels **b)** and **d)**. **(e)** Monthly anomalies of Chl-a (green line) for the period 2012–2018 and MLD (purple line) for the period 2012–2015 over the eastern Pemba Channel, relatively to their respective seasonal cycles. The Pearson correlation coefficients at no lag (called here R), p-values at no lag (caller here P) and number of points in the timeseries (N) of the two parameters are indicated in the pink boxes. Note that the p-value tests the hypothesis of no correlation. The p-value is the probability of getting a correlation as large as the observed value, when the true correlation is zero. If the p-value is less than 0.05, then the correlation R is significant at the 95% confidence level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2020; Painter et al., 2020), and hence could act in addition to the mixing mechanism. Regardless of the main factor, it is clear that the phytoplankton biomass (main source of food for the mackerel) variations and bloom timing are tied to the seasonal cooling, which is associated with both upper-ocean mixing and upwelling. More importantly the variations in biophysical parameters are consistent with that of the mackerel fish catch.

4. Conclusions and perspectives

This study demonstrates the close links of mackerel fish catch variations with remotely-sensed phytoplankton biomass in the eastern Pemba Channel in relation to the physical conditions (SST and upper ocean mixing). During the SE monsoon, maximum phytoplankton biomass (*Chl-a)* and low SST values are observed over most of the Pemba Channel. Conversely, low *Chl-a* is seen in the NE monsoon when the temperatures are higher. There is a localized patch of cooler waters associated with elevated *Chl-a*, relative to surroundings waters, confined along the eastern Pemba Channel coastline during the SE monsoon.

Within the eastern Pemba Channel, the mackerel variability is coherent with *Chl-a* and SST seasonal variations, where a strong positive (negative) correlation was observed between mackerel catch and *Chl-a* (SST), at one-month lag. These relationships are conserved at the interannual scale when comparing the monthly and annual means of these parameters. These findings indicate that mackerel depend on phytoplankton biomass (*Chl-a*) availability either directly or via zooplankton. Their abundance and seasonality are highly influenced by the environmental factors (*Chl-a* and SST) in the eastern Pemba Channel. The inverse relationship between SST and *Chl-a* in the seasonal cycle, suggests that productivity in the eastern Pemba Channel could be driven by mixing which affects *Chl-a*. Comparisons of monthly MLD and *Chl-a* anomalies strengthen the argument that mixing contributes to bringing up colder nutrient-rich waters from greater depths to the surface. However, mixing is likely acting alongside other drivers such as upwelling.

The fact that warmer SST conditions result in lower ocean productivity and reduced mackerel abundance, could inform on how climate change might affect this fishery. The increase of ocean temperature could negatively affect the growth and reproduction of small pelagics of the Pemba Channel (Sekadende et al., 2020). Over the last 2-3 decades, the Tanzanian coastal waters have been experiencing a long-term upward temperature and downward Chl-a trends, with an average SST increase of 0.1 °C/decade - accelerating to 0.15 °C/decade during 2010–2019 - and a Chl-a decline of 0.1 mg/m^3/decade (Sekadende et al., 2020). In the future climate projections scenarios, the SST of the Western Indian Ocean is projected to increase (IPCC, 2013). The projected warming along the Tanzanian coast until the end of the 21st century is up to 5 °C and associated with a reduced productivity (Jacobs et al., Personal Communication). All this suggests that a reduction in the mackerel stocks is likely to occur in Pemba with the regional warming. This impact would necessitate management interventions and adaptation measures, such as a reduced effort in order for the mackerel fishery to remain sustainable.

Although this study has indicated close links between SST, Chl-a and mackerel catch, towards the end of the study period the interannual variations and the perspectives obtained from local fisheries officers suggest that the increased fishing effort may be becoming more important in influencing the number of mackerel caught. Monitoring the SST and Chl-a using remote sensing could provide an indication of the expected catch in any particular year if the fish is exploited below a sustainable level, but this needs to be complemented by conducting a quantitative stock assessment of the fishery and monitoring the fishing effort as well. This is particularly challenging, since this is an open access fishery, controlled by socio-economic factors that makes the implementation of management measures difficult. At some stage the fishing effort may exceed the available catch at which point some active management of the mackerel fishery may need to be undertaken (e.g., extending the Pemba Channel Conservation Area – PECCA). To achieve this goal, planning for the future of the eastern Pemba Channel small pelagic fisheries is required by the relevant Zanzibar authorities.

Management of fisheries resources in Pemba marine waters is coordinated by the Zanzibar Ministry of Agriculture, Natural resources, Livestock and Fisheries, based mainly on the legal and institutional frameworks (policies, acts, regulations, by laws). A comprehensive fisheries management plan for small pelagic fisheries has been developed by the MANRLF (Department of Fisheries Development, 2019). A number of management measures are in use for the pelagic fisheries (Maina and Osuka, 2014). For example, in order to conserve the fishery resources within PECCA, certain fishing gears (such as seine nets) are not allowed and no take zones have been declared in some areas within the PECCA (e.g. waters around Misali Island), where fishing activities are highly restricted (Pemba foundation, 2016).

Satellite derived information on ocean colour can be an important aid in monitoring seasonal changes in productivity to address management objectives, if integrated and used as ecological indicators (Platt and Sathyendranath, 2008). Knowledge gained from understanding seasonal and interannual variability of mackerel catches and the biophysical drivers can be applied in identifying areas and seasons with high productivity that are crucial for management measures such as introducing spatial and seasonal closures. Additionally, more refined predictive models will need to be developed in the future, to provide improved estimates of the errors associated with the prediction.

Responsible institutions may benefit from including in their medium-to-long term management actions capacity building for the fisheries resource managers to be able to acquire and interpret the remotely sensed data which can be directly linked to the catch as phytoplankton biomass. Active participation of local fishers in management of mackerel and other small pelagic fisheries is also crucial for the management to succeed. They are the immediate users of the fish resource and possess vital traditional knowledge in the ecology and habitats for the fishery. Thus, their role should be a key part of the components of any management plans.

The methods and analysis used in this study could also be applied to inform the variability of other local small pelagic fisheries; and likely generalized to world regions with a similar socio-economic context (i.e., dependent on marine resources for their livelihood). As a next step, the synergetic use of satellite observations, in the expectation of their continuous improvement, with other data sources and modelling tools should enable a better understanding and prediction of the environmental factors influencing variability of small pelagic resources. This would offer promising possibilities for the sustainable use of this valuable fish resource for the regional food security under the accelerated impacts of climate change and overfishing pressure.

Authors contribution statement

H.J.K. wrote the initial draft of the paper and F.J. was responsible for the coordination of all contributions and revision. F.J. and Me.S. assisted in writing the manuscript. D.E.R., F.J., and H.J.K. developed the study concept, analysed the data and formatted figures. H.J.K., D.E.R., Y.S., Me.S., Z.J., E.P., F.N., and M.K. contributed to the analysis and interpretation of the results. Z.J. provided the model data and F.N. helped in acquiring satellite *Chl-a* data. Mw.S. assisted in conducting the survey. E. P. coordinated the research activity planning. All authors have reviewed the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2021.105593.

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